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Soil-profile organic carbon and total nitrogen during 12 years of pasture management in the Southern Piedmont USA

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ABSTRACT

Soil organic C (SOC) and total soil N (TSN) sequestration estimates are needed to improve our understanding of management influences on soil fertility and terrestrial C cycling related to greenhouse gas emission. We evaluated the factorial combination of nutrient source (inorganic, mixed inorganic and organic, and organic as broiler litter) and forage utilization (unharvested, low and high cattle grazing pressure, and hayed monthly) on soil-profile distribution (0–150 cm) of SOC and TSN during 12 years of pasture management on a Typic Kanhapludult (Acrisol) in Georgia, USA. Nutrient source rarely affected SOC and TSN in the soil profile, despite addition of 73.6 Mg ha^{-1} (dry weight) of broiler litter during 12 years of treatment. At the end of 12 years, contents of SOC and TSN at a depth of 0–90 cm under haying were only 82 $\pm$ 5% (mean $\pm$ S.D. among treatments) of those under grazed management. Within grazed pastures, contents of SOC and TSN at a depth of 0–90 cm were greatest within 5 m of shade and water sources and only 83 $\pm$ 7% of maximum at a distance of 30 m and 92 $\pm$ 14% of maximum at a distance of 80 m, suggesting a zone of enrichment within pastures due to animal behavior. During 12 years, the annual rate of change in SOC (0–90 cm) followed the order: low grazing pressure (1.17 Mg C ha^{-1} year^{-1}) > unharvested (0.64 Mg C ha^{-1} year^{-1}) = high grazing pressure (0.51 Mg C ha^{-1} year^{-1}) > hayed ($-$0.22 Mg C ha^{-1} year^{-1}). This study demonstrated that surface accumulation of SOC and TSN occurred, but that increased variability and loss of SOC with depth reduced the significance of surface effects.

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1. Introduction

Sequestration of soil organic C (SOC) and conservation of N in soil are of keen scientific and political interests as management pathways to help mitigate the emission of greenhouse gases (i.e., CO_2 and N_2O), which contribute to global warming (Izaurralde et al., 2001). Total soil N (TSN) is associated with SOC and plays a key role in building soil fertility and enhancing soil productivity. The primary factors affecting SOC and TSN are (1) climatic conditions, such as temperature and precipitation, (2) plant productivity, (3) soil texture and its association with internal drainage, and (4) agricultural management practices, especially those that affect the type and amount of organic matter inputs to soil and the extent of soil disturbance (Paul et al., 1997). Agricultural practices are important variables within a given climatic zone that control (1) the quantity, quality, and placement of organic matter inputs via crop selection, crop rotation, fertilization, organic amendment, and tillage type and frequency and (2) the loss of organic matter via plant harvest, erosion, and enhanced microbial decomposition (Magdoff and Weil, 2004).

In the warm, humid region of the southeastern USA, pastures are recognized as an important land use capable of storing a large quantity of SOC and TSN (Franzluebbers, 2005). However, only few data are available that describe how pasture management can influence the long-term dynamics of SOC and TSN. In the southeastern USA (including the states of AL, AR, DE, FL, GA, LA, MD, MS, NC, SC, TN, and VA), pasture land accounts for 13.8 Mha or 34% of the total farm land (USDA-National Agricultural Statistics Service, 2004). Establishment of switchgrass (*Panicum virgatum* L.) for bioenergy production resulted in a rate of SOC sequestration to a depth of 30 cm ranging from 0.5 Mg C ha^{-1} year^{-1} during 10 years in Alabama (Ma et al., 2000) to 2.9 Mg C ha^{-1} year^{-1} during 5 years at five locations in eastern Texas (Sanderson et al., 1999). During the first 5 years of bermudagrass (*Cynodon dactylon* L.) management in Georgia, SOC sequestration in the surface 6 cm was 1.4 Mg C ha^{-1} year^{-1} when grazed by cattle in summer and 0.5 Mg C ha^{-1} year^{-1} when not grazed (Franzluebbers et al., 2001).

Relatively little is known about SOC and TSN sequestration throughout the soil profile. Whether positive effects of pasture management on SOC and TSN in surface soil might continue to

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accumulate at deeper layers has received relatively little attention, despite a recognition that deep-rooted plant species might contribute significantly to SOC sequestration (Fisher et al., 1994). Sequestration of SOC and TSN deeper in the soil profile could provide longer-term benefits that would not be as susceptible to loss from decomposition and erosion with future surface-soil disturbances. A difference in SOC between adjacent cropland and 5-years-old conservation reserve grassland in the Great Plains USA was detected in various increments to 40-cm depth, but not in depth increments from 40 cm to 300 cm below the surface (Gebhart et al., 1994). Summed to 100-cm depth, SOC content was not different between cropland and conservation reserve. In a shortgrass-steppe with 56 years of grazing in Colorado, SOC was not different between unharvested and lightly grazed rangeland at any soil depth increment to 90 cm (Reeder et al., 2004). In contrast, SOC was greater in four of seven depth increments to 90 cm under heavily grazed compared with unharvested rangeland. At the end of 12 years of grazing on a previously ungrazed mixed-grass rangeland in Wyoming, SOC and TSN were greater with light and heavy stocking than an ungrazed exclosure at a depth of 0–30 cm, but statistically similar between treatments at a depth of 0 cm and 60 cm (Schuman et al., 1999). At the end of 5 years of bermudagrass management in Georgia, SOC sequestration occurred in the surface 15 cm and small declines (although statistically significant in only 6 of 24 comparisons) occurred at lower depths to 150 cm (Franzluebbers and Stuedemann, 2005). Likewise, TSN sequestration occurred primarily in the surface 15 cm and both small declines (significant in 2 of 24 comparisons) and small increases (significant in 2 of 24 comparisons) occurred at lower depths. These data suggest that relatively low SOC and TSN concentrations with increasing depth compared with surface-soil concentrations combined with equally high random variation would limit our ability to detect management-induced changes in SOC and TSN sequestration throughout the profile.

We hypothesized that detailed research with at least a decade of consistent management would be needed to detect significant changes in soil-profile distribution of SOC and TSN under pastures. A comparison of analysis techniques indicated that linear regression of SOC and TSN changes with time produced lower variation than point-in-time measurements at the end of an evaluation period (Franzluebbers and Stuedemann, 2005). Therefore, our objectives were to (1) compare the effects of nutrient source and forage utilization strategies on SOC and TSN at the end of 12 years of pasture management, (2) determine the rates of change in SOC and TSN with various depth increments throughout the soil profile based on sampling at 0, 5, and 12 years of management, and (3) quantify the extent of potential spatial redistribution of SOC and TSN induced by cattle behavior within a pasture.

2. Materials and methods

2.1. Site characteristics

A 15-ha upland field (33°22′N, 83°24′W) in the Greenbrier Creek subwatershed of the Oconee River watershed near Farmington Georgia USA had previously been conventionally cultivated with various row crops for several decades prior to grassland establishment by sprigging of ‘Coastal’ bermudagrass [*Cynodon dactylon* (L.) Pers.] in 1991. Grassland management from 1991 to 1994 consisted of a low level of fertilizer input and periodic mowing to control growth. From 1994 to the end of summer in 1998, bermudagrass was the dominant forage (Franzluebbers et al., 2004). ‘Georgia 5’ tall fescue (*Lolium arundinaceum* Schreb. S.J. Darbyshire) was drilled (approx. 28 kg seed ha^{-1}) directly into existing bermudagrass sod during November 1998, 1999, and 2000. Dry winter conditions and shallow seed placement prevented adequate establishment in 1998 and 1999 and the need for repeated sowing. Long-term mean annual temperature was 16.5 °C, rainfall was 1250 mm, and potential pan evaporation was 1560 mm. Dominant soils at the site were Madison, Cecil, and Pacolet sandy loam [fine, kaolinitic, thermic Typic Kanhapludults (USDA), Acrisols (FAO)].

2.2. Experimental design

The experimental design was a randomized, complete block with treatments in a split-plot arrangement in each of three blocks, which were delineated by landscape features (i.e., slight, moderate, and severe erosion classes). Main plots were nutrient source ($n = 3$) and split-plots were forage utilization ($n = 4$) for a total of 36 experimental units. Grazed plots (i.e., paddocks) were 0.69 ± 0.03 ha. Spatial design of paddocks minimized runoff contamination and facilitated handling of cattle (*Bos taurus*) through a central roadway. Each paddock contained a 3 × 4 m shade, mineral feeder, and water trough placed in a line 15-m long at the highest elevation. Unharvested and hayed exclosures (100 m^2) were randomly placed side-by-side in paired low- and high-grazing pressure paddocks of each nutrient source.

Nutrient-source treatments from 1994 to 1998 were (1) inorganic fertilizer as NH_4NO_3 broadcast in May and July, (2) crimson clover (*Trifolium incarnatum* L.) cover crop + inorganic fertilizer (half of N assumed fixed and released by clover cover crop during spring and the other half as NH_4NO_3 broadcast in July), and (3) chicken (*Gallus gallus*) broiler litter broadcast in May and July. Nutrient-source treatments were modified after the first 5 years of management (Table 1). Fertilizer application was targeted to supply 200 kg N ha^{-1} $year^{-1}$ during the first 5 years [see Franzluebbers and Stuedemann (2005) for management details] and targeted to supply 270 kg N ha^{-1} $year^{-1}$ during the next 7 years. From 1999 to the end of summer 2005, the three nutrient sources were: (1) inorganic fertilizer as NH_4NO_3 broadcast in three applications in February–April, May–July and September–November, (2) single application of broiler litter broadcast in February–April and supplemented with inorganic fertilizer as NH_4NO_3

Table 1
Characteristics and rates of fertilizer sources applied to pastures

Year	Inorganic	Low broiler litter[a]		High broiler litter	
	kg N ha^{-1}	Mg C ha^{-1}	kg N ha^{-1}	Mc C ha^{-1}	kg N ha^{-1}
1994	211	NA	211	1.83	195
1995	202	NA	101	2.05	216
1996	250	NA	132	1.69	164
1997	238	NA	120	1.93	223
1998	224	NA	111	1.66	172
1999	276	0.96	337	2.87	393
2000	285	0.90	281	2.69	300
2001	267	0.96	291	3.00	318
2002	270	1.11	289	3.17	288
2003	283	1.11	302	3.36	333
2004	271	1.11	301	2.74	294
2005[b]	177	1.33	219	2.28	220
Mean annual	246 ± 36	0.62 ± 0.56	261 ± 44	2.44 ± 0.60	260 ± 71

NA is not applicable.
[a] Low broiler litter treatment was inorganic only in 1994 and crimson clover (*Trifolium incarnatum* L.) cover crop + inorganic fertilizer from 1995 to 1998 with an additional 110 kg N ha^{-1} $year^{-1}$ assumed to be released from biologically fixed N in clover crop biomass from 1995 to 1998.
[b] Fertilizer treatments were terminated at the end of summer in 2005, and therefore, represented only two applications instead of three applications from 1999 to 2004.

broadcast in May–July and September–November, and (3) multiple application of broiler litter broadcast three times in February–April, May–July, and September–November.

Forage utilization regime consisted of (1) unharvested biomass (cut and left in place at the end of growing season during Years 1–5 and left unmanaged during Years 6–12, except for an occasional woody plant removal), (2) low grazing pressure targeted to maintain 3.0 Mg ha^{-1} of forage, (3) high grazing pressure targeted to maintain 1.5 Mg ha^{-1} of forage, and (4) hayed monthly to remove above-ground biomass at 5-cm height. Yearling Angus steers grazed paddocks during a 140-d period from mid-May until early October during Years 1–5 (mean body weight of 212 kg and density of 5.8 steers ha^{-1} and 8.7 steers ha^{-1} in low and high grazing pressure treatments, respectively). Grazing was extended into spring (March–May) and autumn (mid-October to early January) during Years 6–12 with the presence of tall fescue. Grazing did not typically occur from mid-January to mid-March.

2.3. Sampling and analyses

Soil was sampled in April 1994, February 1999, and February 2006. Soil-profile SOC and TSN in 1994 and 1999 were reported in Franzluebbers and Stuedemann (2005). In February 1999 and 2006, subsampling locations within grazed paddocks were arranged along three semicircles, i.e., at 5, 31 ± 3 m, and 72 ± 10 m from shade/water. Along each of these semicircles, three cores were randomly collected and composited. Two cores were randomly collected and composited in each unharvested and hayed exclosure. The limited number of cores per composite sample could be justified based on the number of factorial arrangements in the study to characterize each of the treatment effects (e.g., in the 2006 sampling alone, a total of 27 cores represented the mean values for low and high grazing pressure and a total of 18 cores represented the mean values for unharvested and hayed treatments. Distance from shade and water sources varied somewhat in each paddock, because of the different shapes of the paddocks and the intent to create three equally sized zones in each paddock. Soil cores (4.1-cm diameter) were extracted with a hydraulic probe mounted on a tractor and sectioned into depth units at 15 cm, 30 cm, 60 cm, 90 cm, 120 cm, and 150 cm. Surface residue was scraped to the side before sampling. Soil samples with roots were air-dried and ground to <2 mm in a mechanical grinder in 1994. In 1999 and 2006, soil was oven-dried (55 °C, 72 h) and initially crushed to pass an 8-mm screen and subsequently a portion of the sample ground to <2 mm in a mechanical grinder prior to total C and N determinations.

Soil was analyzed for total C and N concentration with dry combustion at 1350 °C (Leco CNS-2000, St. Joseph, MI)[1] in 1994 and 1999 and at 950 °C (Leco CN TruSpec, St. Joseph, MI) in 2006. No difference in estimates between instruments was expected, since similar soil standards were used for each calibration. It was assumed that total C was equivalent to SOC because soil pH was ≤6.5 at all soil depths. Samples were analyzed after collection each year. Inorganic N (NH_4–N and NO_3–N) were determined by extraction with 2 M KCl and these values subtracted from TSN to obtain soil organic N (SON).

To assess nutrient source and forage utilization effects, data from multiple samples within an experimental unit (i.e., the three distances from shade/water source) were averaged and not considered a source of variation. The general linear models procedure was used to analyze data (SAS Institute, 1990). Previous research has shown that animal behavior might influence spatial

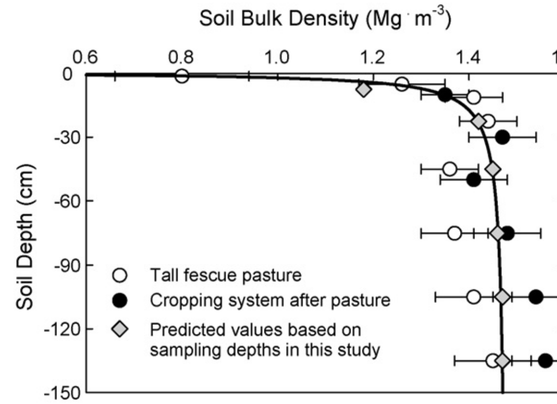

Fig. 1. Soil-profile bulk density distribution from two ancillary studies used to estimate mean bulk density at 0–15, 15–30, 30–60, 60–90, 90–120, and 120–150 cm depths in this study. Bulk density data were taken from studies of Franzluebbers et al. (2000) for tall fescue pasture and Franzluebbers and Stuedemann (2008) for cropping system after pasture.

distribution of soil organic C and N (West et al., 1989; Franzluebbers et al., 2000). Only to assess the impact of animal behavior on potential accumulation of SOC and SON was a separate analysis of variance conducted using zone (i.e., 0–30 m, 30–70 m, and 70–120 m from shade/water) and its interactions with nutrient source and forage utilization as sources of variation. Cumulative SOC and SON contents with depth (i.e., integrated from surface to specified depth) were calculated assuming bulk density of 1.18 Mg m^{-3} at 0–15 cm, 1.42 Mg m^{-3} at 15–30 cm, 1.45 Mg m^{-3} at 30–60 cm, 1.46 Mg m^{-3} at 60–90 cm, and 1.47 Mg m^{-3} at depths below 90 cm. These values were estimated from two different studies conducted on the same soil type at a nearby location (Fig. 1). Some variation in actual bulk density among treatments, replications, and years of sampling may have occurred (±0.1 Mg m^{-3}), but we did not expect it to be significant relative to changes in SOC and SON concentrations. To support this view, soil bulk density in the surface 6 cm was not affected by forage utilization during the first 4 years of the current study (Franzluebbers et al., 2001). Sequestration/loss of SOC and SON contents during 12 years of management was calculated from linear regression with data from 1994 (0 year), 1999 (5 years), and 2006 (12 years). Significant changes in SOC and SON (i.e., different from zero) were determined from the least-square-means output. The analysis at the end of 12 years only allowed for ideal treatment separation, but the analysis across years allowed for actual changes with time. Analysis of variance using SAS 9.1 was conducted separately by depth (i.e., both incremental and cumulative) for SOC and SON concentration and content determined in 2006 (i.e., end of 12 years) and for linear changes in SOC and SON content across years according to the split-plot design with three blocks. All effects were considered significant at $P \leq 0.05$. To summarize responses, we reported mean ± S.D. among various treatment combinations.

3. Results and discussion

3.1. Soil organic C and total N at the end of 12 years

Soil organic C and TSN were highly stratified with depth in this Typic Kanhapludult (Fig. 2) but were almost completely unaffected by the type of nutrient-source regime at the end of 12 years of pasture management (Tables 2 and 3). There was one significant difference in TSN at a depth of 60–90 cm, in which TSN under low broiler litter (0.23 g kg^{-1}) was greater than under high broiler litter (0.21 g kg^{-1}) and inorganic fertilization (0.20 g kg^{-1}) (Fig. 2;

[1] Trade and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the U.S. Department of Agriculture.

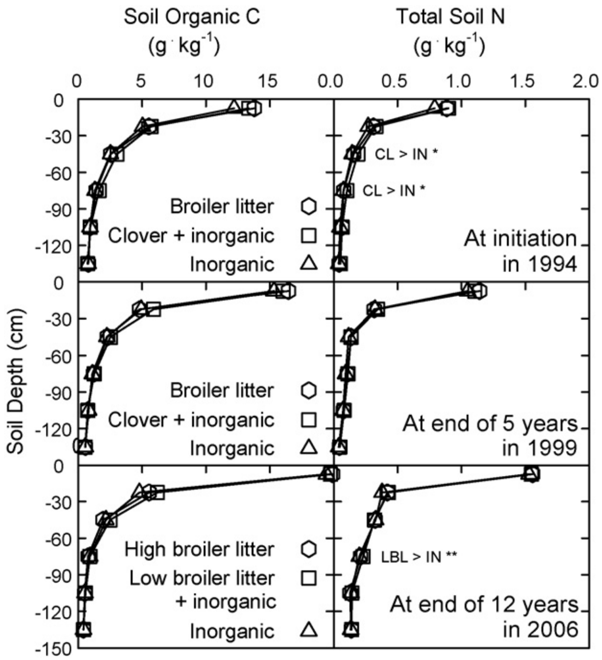

Fig. 2. Soil-profile organic C and total soil N distribution as affected by fertilization regime in 1994, 1999, and 2006. * and ** indicate significance between means within a depth at $P \leq 0.05$ and $P \leq 0.01$, respectively. CL is clover + inorganic, IN is inorganic, LBL is low broiler litter + inorganic.

Table 3). This effect was also present at the beginning of the study (Fig. 2), suggesting unequal TSN among paddocks prior to experimental manipulation. Soil inorganic N (NO_2–N + NO_3–N + NH_4–N) at the end of 12 years averaged 16 mg kg^{-1}, 9 mg kg^{-1}, 1, 10 mg kg^{-1}, 11 mg kg^{-1}, 13 mg kg^{-1}, and 14 mg kg^{-1} at depths of 0–15 cm, 15–30 cm, 30–60 cm, 60–90 cm, 90–120 cm, and 120–150 cm depths, respectively, and therefore, contributed an average of 1.0%, 2.3%, 3.1%, 5.1%, 9.5%, and 10.4% to TSN, respectively. Summed to various depths, SOC and TSN were not different among nutrient-source regimes (Tables 2 and 3). Therefore, whether sufficient N fertilizer came from inorganic or organic sources, there was no effect on SOC and TSN. This result is somewhat surprising, given the relatively large input of C from broiler litter throughout the study (Table 1).

Although not significant, there was an indication for SOC sequestration due to broiler litter application of 1.10 ± 6.70 Mg C ha^{-1} (mean ± S.D. among forage utilization means) and TSN loss of 353 ± 661 kg N ha^{-1}, when calculated as the difference between high broiler litter and inorganic fertilization at a depth of 0–60 cm at the end of 12 years of management. The non-significant sequestration of SOC with broiler litter represented only 4% of the total C applied in broiler litter. The trend for slightly increasing SOC with broiler litter was consistent with that reported earlier in this study (Franzluebbers et al., 2001; Franzluebbers and Stuedemann, 2005). With 21 ± 4 years of broiler litter application to pastures in Alabama, significant SOC sequestration was recorded, equivalent to 8% of the C applied (Kingery et al., 1994). From a review of crop and grazing land studies in the southeastern USA, SOC sequestration was equivalent to 0.26 ± 2.15 Mg C ha^{-1} year^{-1} (Franzluebbers, 2005). Sequestration of SOC with animal manure application was equivalent to 0.20 Mg C ha^{-1} year^{-1} in Italy (Govi et al., 1992) and 0.50 Mg C ha^{-1} year^{-1} in England (Webster and Goulding, 1989). In a review of literature on manure addition to soil, Franzluebbers and Doraiswamy (2007) reported that soil in temperate or frigid regions retained 23 ± 15% of C applied as manure, while soil in thermic regions retained only 7 ± 5% of C applied. The value of 4% found in this study (equivalent to 0.09 Mg C ha^{-1} year^{-1}) is relatively consistent with the literature.

Soil organic C and TSN at the end of 12 years were primarily affected by forage utilization and sampling zone within the surface 15 cm of soil (Tables 2 and 3). Soil organic C was greater under grazed than under ungrazed systems (20.7 g kg^{-1} vs. 16.5 g kg^{-1}) and was greater under unharvested than under hayed manage-

Table 2
Soil organic C concentration by depth increments and soil organic C content summed across depths as affected by forage utilization and zone of sampling at the end of 12 years of management in February 2006

Forage utilization	Zone	Incremental depth (cm)						Cumulative depth (cm)				
		0–15	15–30	30–60	60–90	90–120	120–150	0–30	0–60	0–90	0–120	0–150
		g kg^{-1}						Mg ha^{-1}				
Unharvested (UH)	NA	18.2	5.4	2.5	1.0	0.6	0.3	43.8	54.8	59.2	61.6	63.2
Low grazing pressure (LGP)	Shade	23.5	5.4	2.0	0.7	0.4	0.3	53.1	61.7	64.8	66.4	67.7
Low grazing pressure	Mid	19.1	6.0	2.2	0.9	0.5	0.5	46.5	56.0	59.9	62.2	64.3
Low grazing pressure	Far	22.3	7.0	2.8	1.3	0.8	0.6	54.3	66.3	71.8	75.2	77.7
High grazing pressure (HGP)	Shade	24.1	5.8	2.4	0.9	0.8	0.4	54.9	65.3	69.1	72.5	74.2
High grazing pressure	Mid	17.9	4.3	1.8	0.7	0.4	0.3	40.7	48.3	51.3	53.2	54.7
High grazing pressure	Far	17.6	4.9	2.0	0.7	0.5	0.4	41.7	50.3	53.5	55.6	57.4
Hayed (H)	NA	14.8	5.3	2.1	0.8	0.5	0.5	37.6	46.6	50.3	52.5	54.5
Least significant difference ($P = 0.05$)		3.1	2.1	0.9	0.3	0.4	0.3	8.5	10.8	11.3	11.9	12.4
Coefficient of variation (%)		17	41	41	40	85	65	19	20	20	20	20
Source of variation	d.f.	Pr > *F*										
Nutrient source (NS)	2	0.95	0.40	0.46	0.25	0.68	0.99	0.72	0.72	0.70	0.68	0.71
Forage utilization/zone (FUZ)	7	<**0.001**	0.36	0.34	**0.02**	0.45	0.49	<**0.001**	**0.002**	**0.002**	**0.001**	**0.002**
FUZ1–grazed vs. ungrazed	1	<**0.001**	0.79	0.65	0.48	0.82	0.88	**0.003**	**0.02**	**0.04**	**0.04**	**0.05**
FUZ2–UH vs. H	1	**0.03**	0.91	0.30	0.35	0.80	0.38	0.14	0.13	0.12	0.13	0.16
FUZ3–LGP vs. HGP	1	**0.05**	0.07	0.30	**0.04**	0.92	0.37	**0.03**	**0.04**	**0.02**	**0.03**	**0.03**
FUZ4–shade vs. mid-far	1	<**0.001**	0.93	0.97	0.32	0.88	0.19	**0.003**	**0.02**	**0.03**	**0.03**	**0.05**
FUZ5–mid vs. far	1	0.18	0.28	0.20	0.08	0.31	0.40	0.15	0.11	0.08	0.07	0.07
FUZ6–FUZ3 × FUZ4	1	0.07	0.08	0.06	**0.01**	**0.03**	0.13	**0.04**	**0.02**	**0.01**	**0.007**	**0.007**
FUZ7–FUZ3 × FUZ5	1	0.12	0.81	0.59	0.19	0.46	0.86	0.26	0.28	0.23	0.21	0.22
NS × FUZ	14	0.36	0.53	0.14	0.80	0.50	0.47	0.52	0.42	0.42	0.44	0.46

Zones were defined by distance from shade and water sources (shade = 5 m, mid = 31 ± 3 m, and far = 72 ± 10 m). NA is not applicable. d.f. is degrees of freedom. Pr > *F* is probability of achieving a greater *F*-value; those <0.05 indicated in bold and underlined.

Table 3
Total soil N concentration by depth increments and total soil N content summed across depths as affected by forage utilization and zone of sampling at the end of 12 years of management in February 2006

Forage utilization	Zone	Incremental depth (cm)						Cumulative depth (cm)				
		0–15	15–30	30–60	60–90	90–120	120–150	0–30	0–60	0–90	0–120	0–150
		g kg^{-1}						Mg ha^{-1}				
Unharvested (UH)	NA	1.40	0.40	0.31	0.22	0.16	0.15	3.33	4.69	5.64	6.33	6.98
Low grazing pressure (LGP)	Shade	1.92	0.47	0.35	0.21	0.13	0.14	4.41	5.91	6.85	7.44	8.03
Low grazing pressure	Mid	1.48	0.38	0.30	0.22	0.13	0.12	3.42	4.73	5.68	6.27	6.79
Low grazing pressure	Far	1.65	0.45	0.34	0.25	0.14	0.15	3.88	5.35	6.42	7.02	7.67
High grazing pressure (HGP)	Shade	1.93	0.43	0.34	0.20	0.15	0.12	4.33	5.79	6.64	7.30	7.84
High grazing pressure	Mid	1.38	0.37	0.31	0.19	0.11	0.13	3.24	4.60	5.45	5.94	6.53
High grazing pressure	Far	1.43	0.42	0.34	0.19	0.12	0.13	3.43	4.91	5.76	6.29	6.88
Hayed (H)	NA	1.15	0.35	0.30	0.23	0.14	0.16	2.79	4.11	5.11	5.75	6.44
Least significant difference (P = 0.05)		0.23	0.12	0.05	0.06	0.06	0.05	0.57	0.64	0.66	0.71	0.78
Coefficient of variation (%)		16	32	18	30	50	40	16	13	12	11	11
Source of variation	d.f.	Pr > F										
Nutrient source (NS)	2	0.96	0.36	0.93	**0.02**	0.81	0.91	0.75	0.89	0.72	0.63	0.67
Forage utilization/zone (FUZ)	7	<**0.001**	0.55	0.52	0.65	0.89	0.83	<**0.001**	<**0.001**	<**0.001**	<**0.001**	<**0.001**
FUZ1—grazed vs. ungrazed	1	<**0.001**	0.22	0.22	0.52	0.29	0.18	<**0.001**	<**0.001**	<**0.001**	**0.002**	**0.01**
FUZ2—UH vs. H	1	**0.03**	0.49	0.69	0.68	0.72	0.75	0.06	0.07	0.12	0.11	0.17
FUZ3—LGP vs. HGP	1	0.13	0.48	0.95	0.08	0.69	0.84	0.15	0.21	0.06	**0.05**	0.07
FUZ4—shade vs. mid-far	1	<**0.001**	0.23	0.26	0.64	0.44	0.87	<**0.001**	<**0.001**	<**0.001**	<**0.001**	<**0.001**
FUZ5—mid vs. far	1	0.17	0.18	0.09	0.53	0.83	0.42	0.11	**0.04**	**0.03**	**0.03**	**0.03**
FUZ6—FUZ3 × FUZ4	1	0.26	0.76	0.59	0.62	0.37	0.69	0.50	0.69	0.56	0.36	0.48
FUZ7—FUZ3 × FUZ5	1	0.43	0.77	0.88	0.53	0.92	0.44	0.48	0.49	0.36	0.42	0.34
NS × FUZ	14	0.28	0.83	0.19	0.75	0.97	0.77	0.38	0.28	0.12	0.14	0.18

Zones were defined by distance from shade and water sources (shade = 5 m, mid = 31 ± 3 m, and far = 72 ± 10 m). NA is not applicable. d.f. is degrees of freedom. Pr > F is probability of achieving a greater F-value; those <0.05 indicated in bold and underlined.

ment (18.2 g kg^{-1} vs. 14.8 g kg^{-1}). These differences were consistent with those reported at the end of 5 years of management (Franzluebbers and Stuedemann, 2005). The difference in SOC between low and high grazing pressure became significant at the end of 12 years (21.6 g kg^{-1} vs. 19.9 g kg^{-1}), but there was no difference in SOC at the end of 5 years (Franzluebbers and Stuedemann, 2005). Total soil N was not different between low and high grazing pressure at the end of 12 years.

At a depth of 0–15 cm, SOC was 25 ± 14% greater (mean ± S.D. among six combinations of nutrient source × grazing pressure) and TSN was 30 ± 10% greater near shade and water sources than farther away. At the end of 5 years of management, similar effects were observed with 19 ± 6% greater SOC and 24 ± 9% greater TSN near shade and water sources than farther away (Franzluebbers and Stuedemann, 2005). Animal behavior was a likely reason for preferential accumulation of SOC and TSN near shade and water sources (West et al., 1989; Franzluebbers et al., 2000). Cattle spend more time near shade and water sources, depositing more feces and urine and avoiding forage in these defecation areas, all of which could contributed to soil organic C and N accumulation. Assuming cattle were to have consumed 50 L per head per day with a mean stocking rate of 5.8 steers ha^{-1} and 8.7 steers ha^{-1}, then 290 L ha^{-1} d^{-1} and 435 L ha^{-1} d^{-1}, respectively, could have been potentially supplied to pastures via urine. Assuming 67% of urine were deposited within the shade/water zone, then 18–26 mm of extra water could have been supplied to this zone during the 140-day summer growing season, which would have been 1–2% of mean annual precipitation of 1250 mm.

Below 15 cm, no other differences in SOC or TSN were observed due to forage utilization, but SOC tended to be greater at the farthest distance from shade and water sources under low grazing pressure (difference was significant below 60 cm with consistent trend nearer the surface) (Table 2). This result was not easily explained, and therefore, could be an unfortunate anomaly from the eroded and undulating landscape that this experiment was laid upon. Lack of significant differences in SOC and TSN among nutrient source and forage utilization regimes below the surface 15 cm of soil suggests that either (1) differences in rooting patterns, and subsequent conversion into organic C and N, were not greatly affected by management, (2) detectable changes in SOC and TSN are simply not readily observable in this warm-humid region, in which organic inputs are rapidly decomposed and recycling of nutrients is very active near the soil surface, or (3) insufficient time had elapsed to detect potential changes. These results provide evidence to suggest that management-induced surface changes in SOC and TSN in the southeastern USA are of most critical importance, countering the notion that deep-profile changes in SOC must be accounted (Baker et al., 2007). Although deeper rooting in ungrazed compared with grazed grasslands might be possible (Schuster, 1964), we did not see any reflection of this potential rooting change on SOC and TSN with depth. Other studies have found few differences in grass root distribution between grazed and ungrazed grasslands (McNaughton et al., 1998; Lodge and Murphy, 2006) suggesting that above-ground forage removal (haying) and processing (grazing and manure deposition) may not always adversely affect below-ground C inputs and decomposition dynamics.

The large, significant effects of forage utilization and sampling zone on SOC and TSN were mostly retained throughout the soil profile when contents were summed to various depths (Tables 2 and 3). The LSD separating SOC means increased from 8.5 Mg C ha^{-1} at a depth of 0–30 cm to 12.4 Mg ha^{-1} at a depth of 0–150 cm (Table 2). The larger variance with depth means that significant differences at the surface may not be considered statistically significant throughout the soil profile or, as in our case, would require an additional sequestration rate of 0.33 Mg C ha^{-1} year^{-1} to maintain significance. Limiting calculations only to the 0–30 cm depth, the difference in SOC between grazed and ungrazed systems suggested that grazing by cattle contributed the equivalent of 4.6 ± 5.0 Mg C ha^{-1} of additional SOC than unharvested grass and the equivalent of 10.9 ± 3.5 Mg C ha^{-1} of additional SOC than hayed grass. Comparable calculations for TSN

Table 4
Linear rate of change in soil organic C content by depth increments and summed across depths as affected by fertilization, forage utilization, and their interactions during 12 years of management (sampling periods at 0, 5, and 12 years)

Forage utilization	Nutrient source	Incremental depth (cm)						Cumulative depth (cm)				
		0–15	15–30	30–60	60–90	90–120	120–150	0–30	0–60	0–90	0–120	0–150
		Mg ha^{-1} year^{-1}						Mg ha^{-1} year^{-1}				
Unharvested (UH)	Inorganic	0.72	−0.17	−0.26	−0.22	−0.16	−0.18	0.54	0.28	0.07	−0.09	−0.26
Low grazing pressure (LGP)	Inorganic	1.20	−0.04	−0.20	−0.20	−0.16	−0.14	1.15	0.95	0.75	0.59	0.45
High grazing pressure (HGP)	Inorganic	0.89	−0.16	−0.23	−0.24	−0.12	−0.09	0.73	0.50	0.26	0.14	0.04
Hayed (H)	Inorganic	0.31	−0.07	−0.10	−0.14	−0.11	−0.13	0.24	0.14	0.00	−0.11	−0.24
Unharvested	Low broiler litter	0.42	0.10	0.20	−0.05	−0.13	−0.14	0.52	0.73	0.68	0.55	0.41
Low grazing pressure	Low broiler litter	1.34	0.30	0.05	−0.19	−0.16	−0.14	1.64	1.69	1.50	1.34	1.20
High grazing pressure	Low broiler litter	1.13	0.00	−0.25	−0.23	−0.11	−0.15	1.13	0.88	0.65	0.54	0.39
Hayed	Low broiler litter	0.08	0.31	−0.16	−0.22	−0.16	−0.04	0.39	0.23	0.00	−0.16	−0.19
Unharvested	High broiler litter	1.23	0.09	−0.17	−0.20	−0.13	−0.14	1.33	1.16	0.96	0.83	0.69
Low grazing pressure	High broiler litter	1.27	0.16	−0.32	−0.19	−0.10	−0.07	1.42	1.10	0.92	0.81	0.74
High grazing pressure	High broiler litter	1.00	−0.10	−0.23	−0.31	−0.19	−0.16	0.90	0.68	0.36	0.17	0.01
Hayed	High broiler litter	0.21	−0.27	−0.35	−0.28	−0.23	−0.17	−0.06	−0.41	−0.68	−0.91	−1.08
Least significant difference ($P = 0.05$)		0.49	0.46	0.43	0.22	0.15	0.11	0.78	1.10	1.22	1.29	1.35
Source of variation	d.f.	Pr > *F*										
Nutrient source (NS)												
NS1—inorganic vs. others	1	0.57	**0.05**	0.61	0.84	0.69	0.66	0.14	0.21	0.27	0.32	0.33
NS2—low vs. high broiler litter	1	0.11	0.06	**0.03**	0.18	0.50	0.39	0.91	0.35	0.28	0.27	0.26
Forage utilization (FU)												
FU1—grazed vs. ungrazed	1	<**0.001**	0.76	0.51	0.31	0.70	0.74	<**0.001**	**0.005**	**0.02**	**0.02**	**0.03**
FU2—UH vs. H	1	<**0.001**	0.90	0.28	0.33	0.51	0.22	**0.006**	**0.02**	**0.02**	**0.02**	**0.04**
FU3—LGP vs. HGP	1	**0.05**	0.08	0.52	0.25	0.98	0.55	**0.03**	0.07	0.06	0.08	0.09
NS1 × FU1	1	0.40	0.95	0.85	0.98	0.65	0.30	0.58	0.75	0.77	0.74	0.81
NS1 × FU2	1	0.33	0.49	0.10	0.11	0.21	0.88	0.31	0.17	0.13	0.11	0.13
NS1 × FU3	1	0.80	0.55	0.76	0.77	0.47	0.13	0.85	0.80	0.78	0.73	0.65
NS2 × FU1	1	**0.02**	0.43	0.61	0.53	0.77	0.06	0.29	0.57	0.69	0.73	0.86
NS2 × FU2	1	**0.04**	0.07	0.53	0.49	0.46	0.07	**0.02**	0.15	0.24	0.23	0.20
NS2 × FU3	1	0.88	0.91	0.18	0.56	0.16	0.30	0.98	0.61	0.72	0.86	0.93

d.f. is degrees of freedom. Pr > *F* is probability of achieving a greater *F*-value; those <0.05 indicated in bold and underlined.

were 458 ± 397 kg N ha^{-1} and 996 ± 244 kg N ha^{-1}, respectively. Compared with unharvested grass, haying would have removed 6.3 ± 7.6 Mg C ha^{-1} and 539 ± 308 kg N ha^{-1} from potential organic matter accumulation during the 12 years of management.

Haying removed forage from the field, but would then be fed to cattle elsewhere. The fate of C and N in hay can be surmised with some calculations and assumptions. Hay harvested during the first 5 years of this study was 7.5 ± 2.1 Mg ha^{-1} year^{-1} and contained 483 ± 24 mg C g^{-1} forage and 19 ± 2 mg N g^{-1} forage (Franzluebbers et al., 2004), which would have resulted in removal of 3.6 Mg C ha^{-1} year^{-1} and 143 kg N ha^{-1} year^{-1}. If 40% of C in hay were collected as cattle manure following feeding elsewhere (Schlesinger, 2000), then 1.4 Mg C ha^{-1} year^{-1} could potentially be available for re-application to land. However, further decomposition of cattle manure would be expected in the field [~10% of C in manure retained as soil organic C (Johnson et al., 2007)], and therefore, hay harvesting, feeding, and redistribution on the land could result in about 0.1 Mg C ha^{-1} year^{-1} (not discounting the CO_2 emissions resulting from cutting, baling, and transporting operations). Cattle grazing directly on pasture would have much greater potential to sequester SOC and TSN than haying.

3.2. Soil organic C and N changes with time

Using linear regression of SOC contents at 0, 5, and 12 years of management, significant increase in SOC occurred at 0–15 cm depth (0.82 ± 0.45 Mg C ha^{-1} year^{-1} (mean ± S.D. among 12 combinations of nutrient source × forage utilization), no change occurred at 15–30 cm depth (0.01 ± 0.18 Mg C ha^{-1} year^{-1}), and significant decrease occurred at all depths below 30 cm (-0.16 ± 0.09 Mg C ha^{-1} year^{-1}) (Table 4). In contrast, SON increased significantly at all depths (Table 5). Across management systems, the change in SOC with time averaged 0.91 Mg C ha^{-1} year^{-1} at a depth of 0–30 cm ($P < 0.001$), 0.74 Mg C ha^{-1} year^{-1} at a depth of 0–60 cm ($P < 0.001$), 0.53 Mg C ha^{-1} year^{-1} at a depth of 0–90 cm ($P < 0.001$), 0.38 Mg C ha^{-1} year^{-1} at a depth of 0–120 cm ($P = 0.009$), and 0.25 Mg C ha^{-1} year^{-1} at a depth of 0–150 cm ($P = 0.10$). The change in SON with time averaged 113 kg N ha^{-1} year^{-1} at a depth of 0–30 cm ($P < 0.001$) and increased to 288 kg N ha^{-1} year^{-1} at a depth of 0–150 cm ($P < 0.001$). The decline in SOC with time below 30 cm depth was consistent with trends reported earlier from initiation to 5 years (Franzluebbers and Stuedemann, 2005). The significant increase in SON with time throughout the soil profile appears to have occurred more during the later part of this study than earlier, since there was little change in TSN content with depth reported from initiation to 5 years (Franzluebbers and Stuedemann, 2005). This later increase was consistent with an average of 34% greater fertilizer N input in the latter 7 years compared with the initial 5 years (Table 1). The small, but significant decline in SOC below 30 cm may have been due to historically declining SOC, carrying over from degradative land use prior to this experiment, i.e., a legacy effect from long-term, inversion-tillage management of cropland. A lag effect from the change in management that occurred in 1991 may be possible. The current restorative pasture phase should not have caused this decline with depth, although the data are suggestive of this possibility. More detailed, long-term research on soil-profile organic C and N changes with management are needed to clarify these issues.

The type of nutrient source rarely induced a change from the mean rate of SOC and SON sequestration at any depth (Tables 4 and 5), except for SOC at depths of 15–30 and 30–60 cm. Change in SOC with time was greater under low broiler litter fertilization than under inorganic fertilization (0.18 Mg C ha^{-1} year^{-1} vs.

Table 5
Linear rate of change in soil organic N content by depth increments and summed across depths as affected by fertilization, forage utilization, and their interactions during 12 years of management (sampling periods at 0, 5, and 12 years)

Forage utilization	Nutrient source	Incremental depth (cm)						Cumulative depth (cm)				
		0–15	15–30	30–60	60–90	90–120	120–150	0–30	0–60	0–90	0–120	0–150
		kg ha^{-1} year^{-1}						kg ha^{-1} year^{-1}				
Unharvested (UH)	Inorganic	89	16	54	56	32	43	105	159	215	248	291
Low grazing pressure (LGP)	Inorganic	118	19	54	41	24	32	137	191	233	257	289
High grazing pressure (HGP)	Inorganic	95	8	62	28	20	28	103	165	193	213	241
Hayed (H)	Inorganic	48	9	69	53	42	33	57	126	179	222	255
Unharvested	Low broiler litter	49	13	64	47	44	35	61	125	173	217	251
Low grazing pressure	Low broiler litter	130	27	63	52	23	33	157	220	273	296	329
High grazing pressure	Low broiler litter	119	22	55	50	29	33	141	196	246	275	308
Hayed	Low broiler litter	24	15	49	57	33	50	39	88	145	178	228
Unharvested	High broiler litter	108	22	58	47	33	41	129	187	234	267	308
Low grazing pressure	High broiler litter	121	20	61	52	29	33	143	204	256	285	318
High grazing pressure	High broiler litter	111	20	64	35	18	30	131	195	230	248	278
Hayed	High broiler litter	41	2	45	48	21	49	42	87	135	156	206
Least significant difference (P = 0.05)		41	20	36	23	20	19	49	69	81	90	103
Source of variation	d.f.	Pr > F										
Nutrient source (NS)												
NS1—inorganic vs. others	1	0.99	0.25	0.74	0.42	0.83	0.30	0.63	0.86	0.71	0.77	0.65
NS2—low vs. high broiler litter	1	0.13	0.54	0.93	0.26	0.14	0.90	0.31	0.50	0.81	0.91	0.94
Forage utilization (FU)												
FU1—grazed vs. ungrazed	1	<**0.001**	0.07	0.64	0.06	**0.01**	**0.007**	<**0.001**	<**0.001**	<**0.001**	<**0.008**	0.06
FU2—UH vs. H	1	<**0.001**	0.15	0.68	0.68	0.44	0.40	<**0.001**	**0.004**	**0.02**	**0.02**	0.06
FU3—LGP vs. HGP	1	0.20	0.29	0.96	0.08	0.57	0.71	0.13	0.30	0.17	0.17	0.20
NS1 × FU1	1	0.11	0.25	0.48	0.07	0.40	0.68	0.08	0.10	0.06	0.06	0.11
NS1 × FU2	1	0.86	0.89	0.16	0.56	0.07	0.06	0.84	0.38	0.57	0.36	0.65
NS1 × FU3	1	0.60	0.51	0.62	0.78	0.91	0.84	0.48	0.81	0.77	0.78	0.77
NS2 × FU1	1	**0.02**	0.92	0.62	0.78	0.33	0.61	**0.04**	0.24	0.28	0.45	0.44
NS2 × FU2	1	0.13	0.11	0.95	0.56	0.96	0.57	0.06	0.19	0.20	0.24	0.25
NS2 × FU3	1	0.94	0.90	0.65	0.37	0.23	0.85	0.91	0.75	0.99	0.80	0.79

d.f. is degrees of freedom. Pr > F is probability of achieving a greater F-value; those <0.05 indicated in bold and underlined.

−0.11 Mg C ha^{-1} year^{-1}) at a depth of 15–30 cm and was greater under low broiler litter than under high broiler litter (−0.04 Mg C ha^{-1} year^{-1} vs. −0.27 Mg C ha^{-1} year^{-1}) at a depth of 30–60 cm. Although not significant, the difference between high broiler litter and inorganic fertilization at a depth of 0–60 cm suggested SOC sequestration due to broiler litter application of 0.16 ± 0.58 Mg C ha^{-1} year^{-1} (mean ± S.D. among forage utilization means) and SON sequestration of 8 ± 32 kg N ha^{-1} year^{-1}, both of which were comparable to estimates based solely on values at 12 years (0.09 ± 0.56 Mg C ha^{-1} year^{-1} and −30 ± 55 kg N ha^{-1} year^{-1}). The non-significant trends for changes in SOC and SON with high broiler litter were thought to be due to manure input and not due to differences in plant growth, since forage productivity during the first 5 years was 13% greater with inorganic fertilizer than with broiler litter (Franzluebbers et al., 2004). It may be possible that the expected increase in SOC and SON with manure application could have been balanced with a priming effect of broiler litter that enhanced SOC and SON decomposition.

The type of forage utilization regime elicited changes in the rate of SOC and SON sequestration at a depth of 0–15 cm only (Tables 4 and 5). The increase in SOC with time was greater with grazed than ungrazed systems (1.14 Mg C ha^{-1} year^{-1} vs. 0.50 Mg C ha^{-1} year^{-1}), with the difference greater under low broiler litter than under high broiler litter. The increase in SOC with time was also greater with unharvested than hayed management (0.79 Mg C ha^{-1} year^{-1} vs. 0.20 Mg C ha^{-1} year^{-1}), with the difference greater under high broiler litter than under low broiler litter. The increase in SOC with time was also greater under low than under high grazing pressure (1.27 Mg C ha^{-1} year^{-1} vs. 1.01 Mg C ha^{-1} year^{-1}). As for SON, the only significant change at a depth of 0–15 cm was for greater rate of SON sequestration with grazed than with ungrazed systems (116 kg N ha^{-1} year^{-1} vs. 60 kg N ha^{-1} year^{-1}).

Summed to various soil-profile depths, the effects that occurred within the surface 30 cm of soil generally remained significant throughout the soil profile (Tables 4 and 5). At a depth of 0–60 cm, SOC sequestration followed the order: low grazing pressure (1.25 Mg C ha^{-1} year^{-1}) > unharvested (0.72 Mg C ha^{-1} year^{-1}) = high grazing pressure (0.69 Mg C ha^{-1} year^{-1}) > hayed (−0.01 Mg C ha^{-1} year^{-1}) (Fig. 3). Sequestration of SON at a depth of 0–60 cm followed a similar order, although with fewer significant differences among treatments: low grazing pressure (205 kg N ha^{-1} year^{-1}) = high grazing pressure (185 kg N ha^{-1} year^{-1}) = unharvested (157 kg N ha^{-1} year^{-1}) > hayed (100 kg N ha^{-1} year^{-1}).

Although forage-utilization-treatment differences in the change of SOC and SON with time were consistently maintained throughout the soil profile, statistical significance of SOC with respect to absolute change from zero declined with increasing profile depth (Fig. 3). To a depth of 90 cm, all management systems except for haying exhibited significant sequestration of SOC. Soil organic N sequestration remained significant in all treatments throughout the soil profile. However, to a cumulative depth of 150 cm, only low grazing pressure produced an estimate of significant SOC sequestration, while hayed management resulted in a net loss of SOC with time. The loss of SOC at lower depths would not logically be explained from current management variables. It is possible that historical cultivation of this landscape may have still been exerting a negative influence on SOC dynamics deeper in the profile. We suppose that there could be a lag effect between organic matter input/output dynamics at the soil surface compared with those occurring lower in the soil profile. There

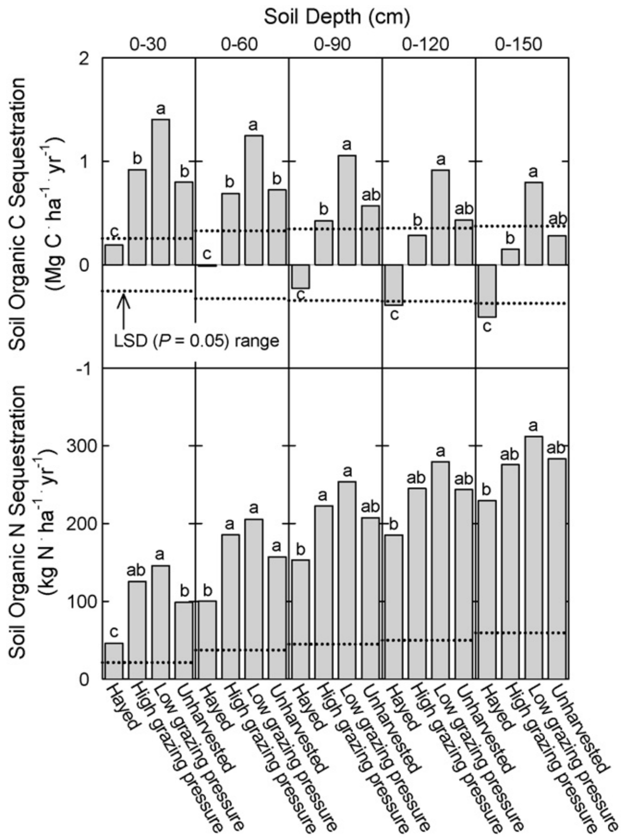

Fig. 3. Soil organic C and N sequestration as affected by forage utilization regime (hayed, low and high grazing pressure, and unharvested) and depth of sampling in the soil profile. Linear regression was used to obtain estimates from values at 0, 5, and 12 years of management. Bars within the same depth increment sharing the same letter are not significantly different at $P = 0.05$.

could be other reasons for the decline in SOC with time at lower depths, although they seem less plausible based on the type and amount of information available.

The difference in temporal estimates between SOC and SON are curious and not easily explained. A relatively high rate of fertilizer N was applied throughout the 12 years of pasture management (256 ± 51 kg N ha^{-1} year^{-1}), which was relatively closely matched in the quantity of SON sequestered to a cumulative soil depth of 150 cm (275 ± 39 kg N ha^{-1} year^{-1}). Certainly small variations in sampling and analytical procedures, as well as in scaling calculations from point estimates to the whole field could have caused the discrepancy between N input and SON sequestration. However, these data suggest that a large fraction of fertilizer N applied was retained within the soil profile. We did not conduct analyses of denitrification and volatilization (nor of input via atmospheric deposition), but it appears that these losses would have been minimal (although inputs may have been substantial). Soil-profile inorganic N was subtracted from all TSN values to obtain SON to avoid accumulation of inorganic N that could have occurred deep in the profile due to root inaccessibility and high fertilizer N inputs. During the first 5 years of management, only small changes in soil-profile inorganic N occurred with time (3 ± 9 kg N ha^{-1} year^{-1}) (Franzluebbers and Stuedemann, 2003). Runoff loss of N was also likely not large, since few runoff events occurred, at least during early years of the study (Franklin et al., 2002). On average soil organic C-to-N ratio of the 150-cm profile declined with time from 16.9 at initiation of the study, to 15.1 at the end of 5 years, and to 9.4 at the end of 12 years. These soil organic C-to-N ratios are generally within the range of values reported in the literature (8–30; Brady and Weil, 1999).

4. Conclusions

Source of nutrients (whether inorganic or organic from broiler litter) had few significant effects on SOC, TSN, and SON changes in the soil profile. As a percentage of C applied in broiler litter, only 4% could be discerned as sequestered in SOC. Forage utilization regime had the most dramatic management effects on SOC, TSN, and SON. Grazing of pasture by cattle led to significantly greater levels of SOC and SON in the surface 15 cm of soil than ungrazed pastures. Therefore, processing of forage through cattle and deposition of feces onto the pasture was beneficial to long-term storage of SOC and SON. Significant redistribution of SOC and TSN was observed, in which areas near shade and water sources were enriched compared to zones farther away. Continuous haying of forage led to the lowest levels of SOC and TSN compared to grazed and unharvested forage. Significant SOC and SON sequestration was observed to a depth of 90 cm (i.e., the primary rooting zone), but increasing variability in SOC concentration limited our ability to declare significant differences below this depth. Small losses of SOC may have occurred deep in the soil profile due to a legacy effect from historical land use, rather than recent management. Long-term perennial pastures grazed by cattle can be considered a significant sink for SOC and SON, helping to mitigate greenhouse gas emissions and build soil fertility. Assuming that the 13.8 Mha of pastureland in the southeastern USA were to have sequestered 0.46 Mg C ha^{-1} year^{-1} to a depth of 0–90 cm as observed in this study, a total of 6.3 Tg C could potentially be stored as a result of grass management in the region, a value similar to that potentially stored if all cropland in the region were converted to no-tillage management.

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